MOS Stack

Lecture 4-5

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Outline

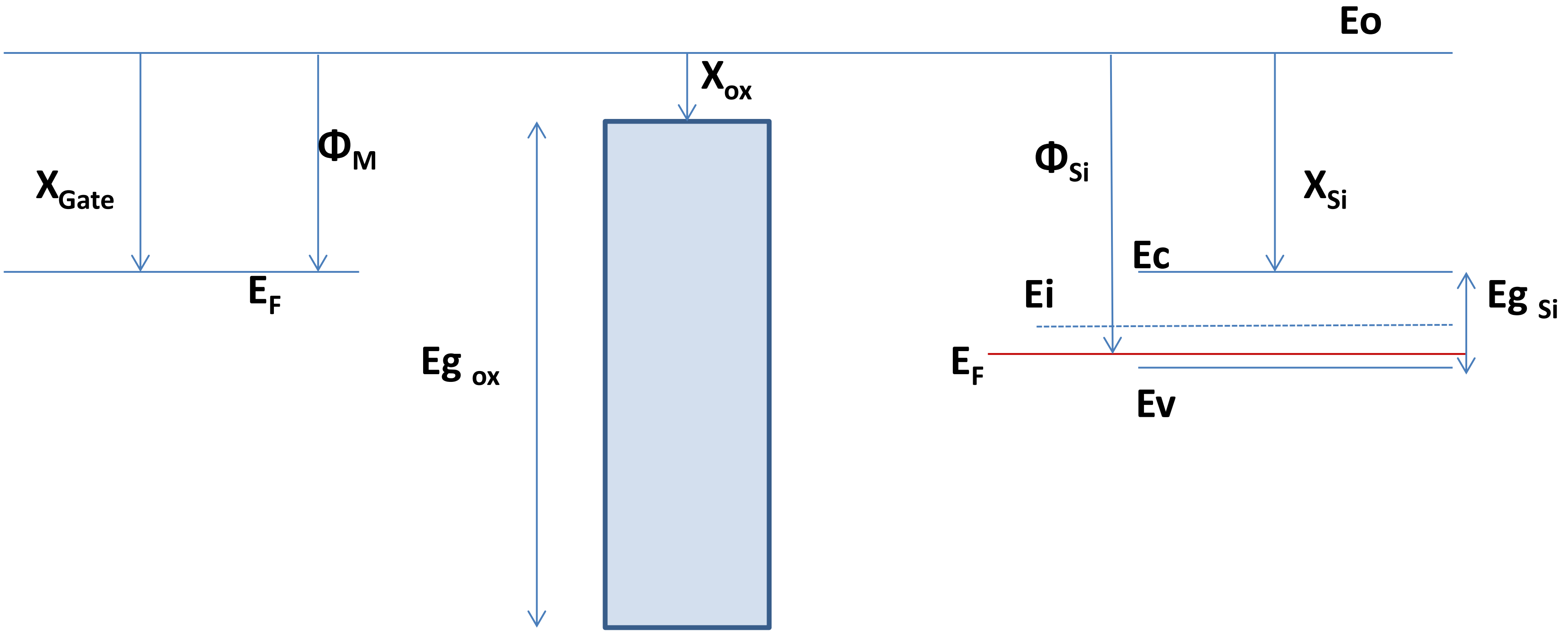
- MOS Band Diagram
- "Classical" Charge Distribution
- Depletion Approximation
- Potential Drop Equation
- Threshold Voltage (V_{th}) and Flatband Volatge (V_{FB})
- Capacitance Voltage (C-V) Characteristics

Reference

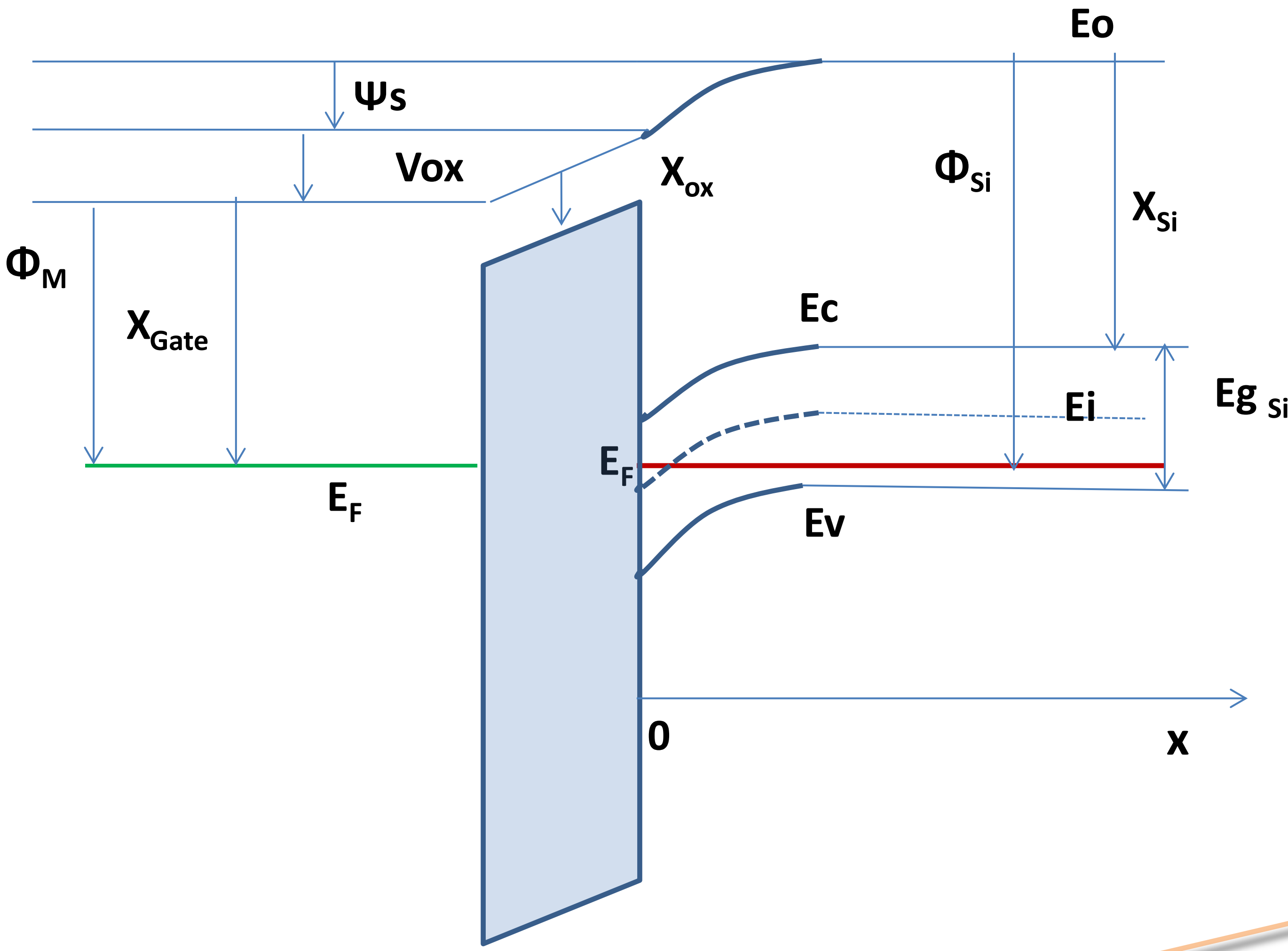
- Fundamentals of Modern VLSI Devices, 2nd Edition

by Yuan Taur , Tak H. Ning, Cambridge Press, 2013

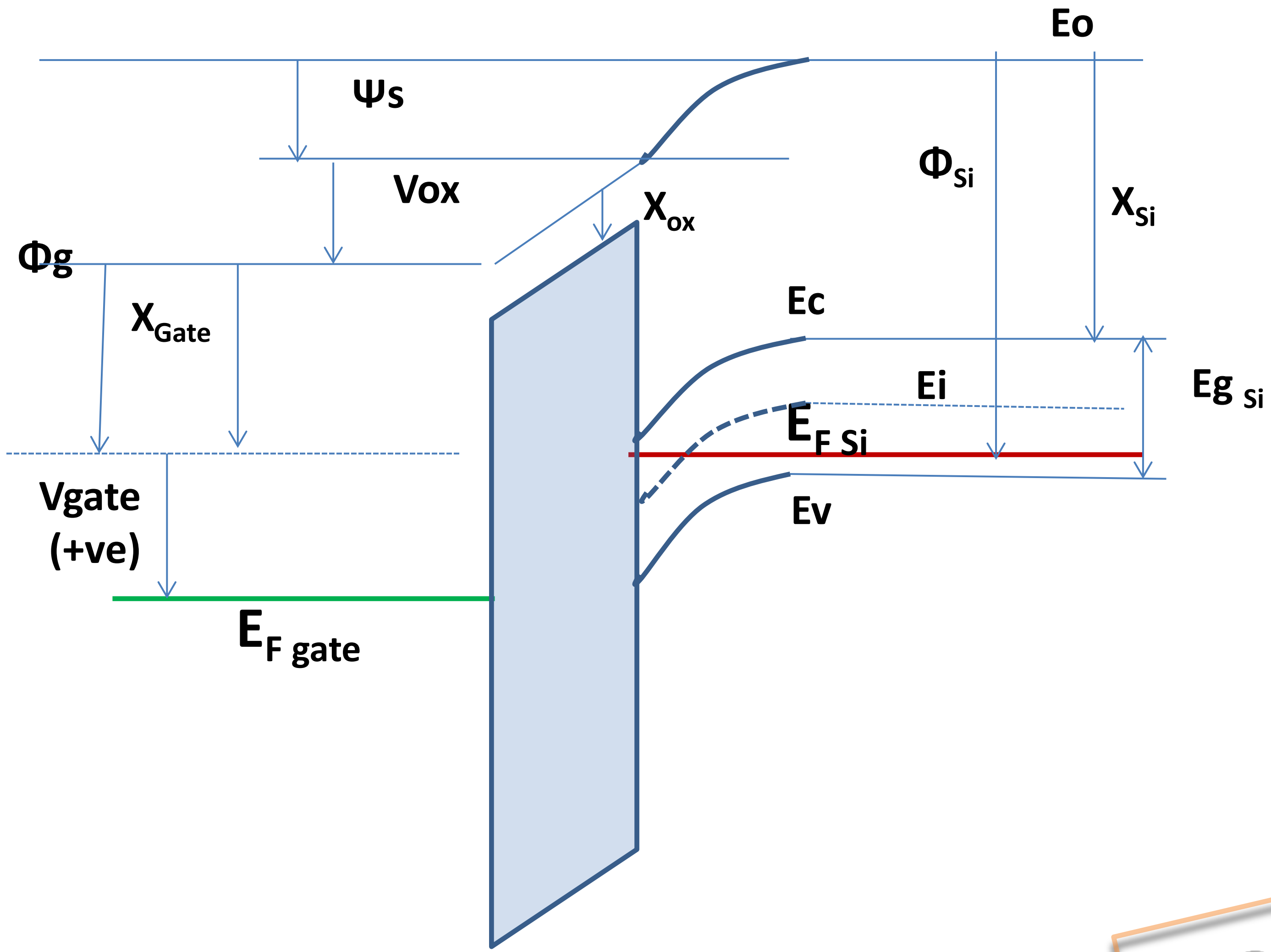
Band Diagram:
Metal-Oxide-Semiconductor



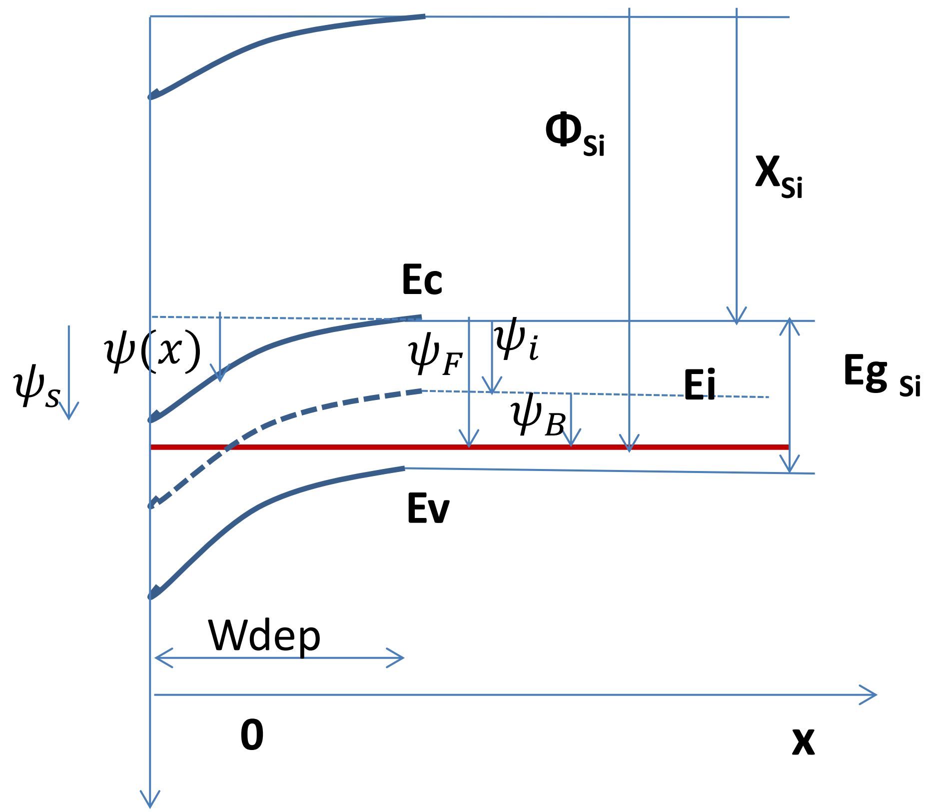
MOS Band Diagram After Contact



Gate Voltage Application



Charge Dependence on Potential



Poisson's Equation for N-MOS Stack

$$\frac{d^2\psi}{dx^2} = -\frac{\rho(x)}{\epsilon}$$

$$= -\frac{q}{\epsilon}\left[p(x) - n(x) + N_D{}^{+}(x) - N_A{}^{-}(x)\right]$$

At $x \rightarrow \infty$: Charge Neutrality: $p_0 - n_0 + N_D{}^{+} - N_A{}^{-} = 0$

$$p(x) = n_i\, e^{q(\psi_F - \psi_i)/k_B T} = n_i\, e^{q(\psi_B - \psi)/k_B T} = N_A\, e^{-q\psi/k_B T}$$

$$n(x) = n_i\, e^{q(\psi_i - \psi_F)/k_B T} = n_i\, e^{q(\psi - \psi_B)/k_B T} = (n_i{}^2/N_A) e^{q\psi/k_B T}$$

$$p_0 \approx N_A\,,\ n_0 = n_i{}^2/p_0 \approx n_i{}^2/N_A$$

$$\frac{d^2\psi}{dx^2} = -\frac{q}{\epsilon}\left[N_A\left(e^{-\frac{q\psi}{k_B T}} - 1\right) - \frac{n_i{}^2}{N_A}\left(e^{\frac{q\psi}{k_B T}} - 1\right)\right]$$

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NMOS Stack Charge Eqn.

Multiply both sides by $\left(\frac{d\psi}{dx}\right) dx \;\; (which\ is\ also\ = dx):$

$$\frac{d^2\psi}{dx^2}\frac{d\psi}{dx}dx = \frac{d}{dx}\left[\frac{d\psi}{dx}\right]\frac{d\psi}{dx}dx = \frac{d\psi}{dx}d\left[\frac{d\psi}{dx}\right]$$

$$\frac{d\psi}{dx}d\left[\frac{d\psi}{dx}\right] = -\frac{q}{\epsilon}\left[N_A\left(e^{-\frac{q\psi}{k_BT}}-1\right)-\frac{n_i^2}{N_A}\left(e^{\frac{q\psi}{k_BT}}-1\right)\right]d\psi$$

Integrate both sides: LHS: from $\frac{d\psi}{dx} = \frac{d\psi_s}{dx}$ at $x = 0$ to $\frac{d\psi}{dx} = 0$ at $x = \infty$

RHS: from $\psi = \psi_s$ at $x = 0$ to $\psi = 0$ at $x = \infty$

$$\left(\frac{d\psi_s}{dx}\right)^2 = \frac{2K_BT\,N_A}{\epsilon_{si}}\left[\left(e^{-\frac{q\psi_s}{k_BT}}+\frac{q\psi_s}{KT}-1\right)+\frac{n_i^2}{N_A^2}\left(e^{\frac{q\psi_s}{k_BT}}-\frac{q\psi_s}{KT}-1\right)\right]$$

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Surface Charge (Q_s)

$$\left(\frac{d\psi_s}{dx}\right)^2 = {F_s}^2$$

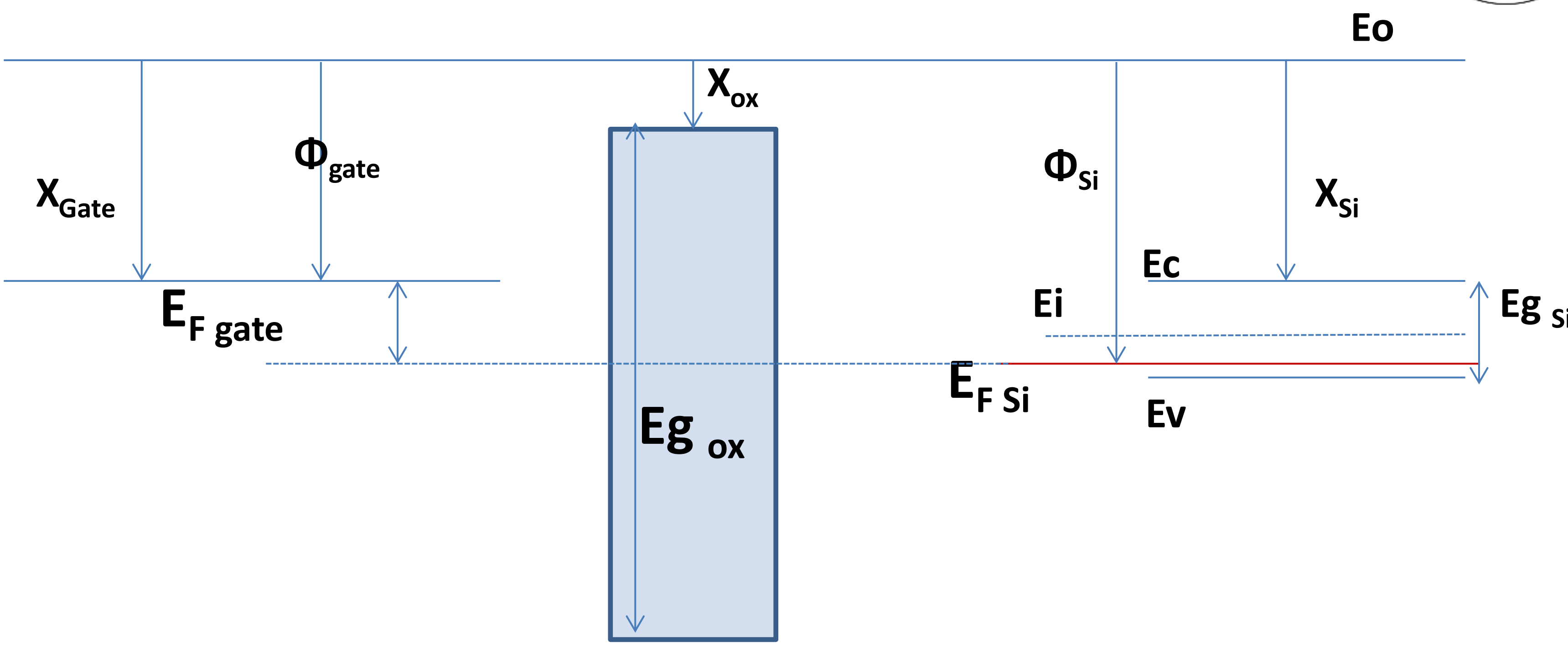
From Poisson's equation:

$$\int_{F_s}^{0} F\, dF = \frac{1}{\epsilon_{Si}} \int_0^{W_{dep}} \rho\, dx \rightarrow \qquad 0 - F_s = \frac{1}{\epsilon_{Si}} Q_s$$

$$Q_s = -\epsilon_{si} F_s = -\epsilon_{si} \sqrt{\left(\frac{d\psi_s}{dx}\right)^2}$$

$$Q_s = \pm\sqrt{2\epsilon_{si} K_B T\, N_A} \left[\left(e^{-\frac{q\psi_s}{k_B T}} + \frac{q\psi_s}{KT} - 1\right) + \frac{{n_i}^2}{NA^2}\left(e^{\frac{q\psi_s}{k_B T}} - \frac{q\psi_s}{KT} - 1\right)\right]^{1/2}$$

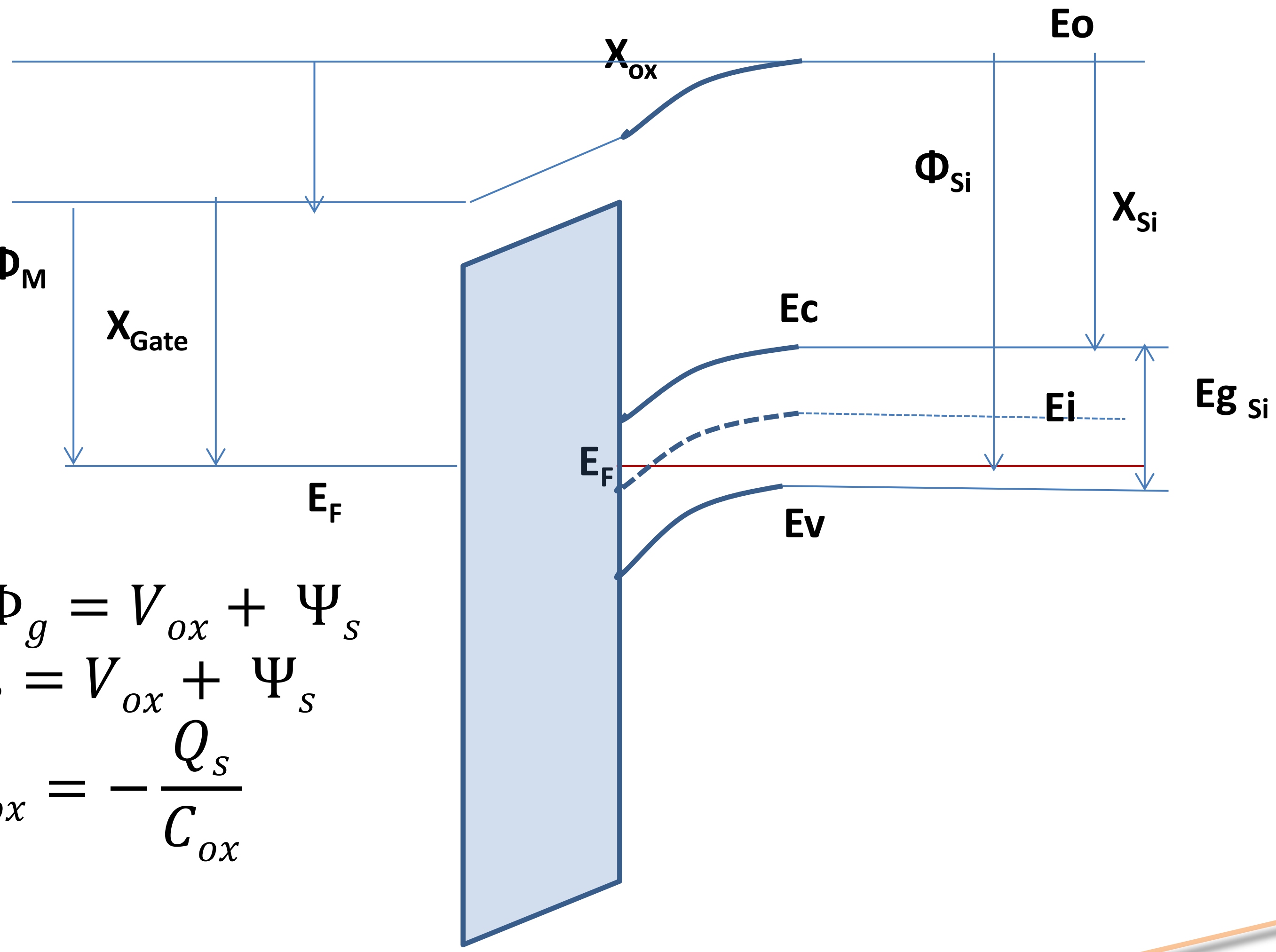
Flatband Voltage (V_{FB})



$$V_{FB} = Gate\ Workfunction - Semiconductor\ Workfunction$$

$$qV_{FB} = \Phi_{gate} - \Phi_{Si} = E_{F\,gate} - E_{F\,Si}$$

Potential Drop Equation: No Applied Gate Voltage



$$\Phi_{si} - \Phi_g = V_{ox} + \Psi_s$$

$$-V_{FB} = V_{ox} + \Psi_s$$

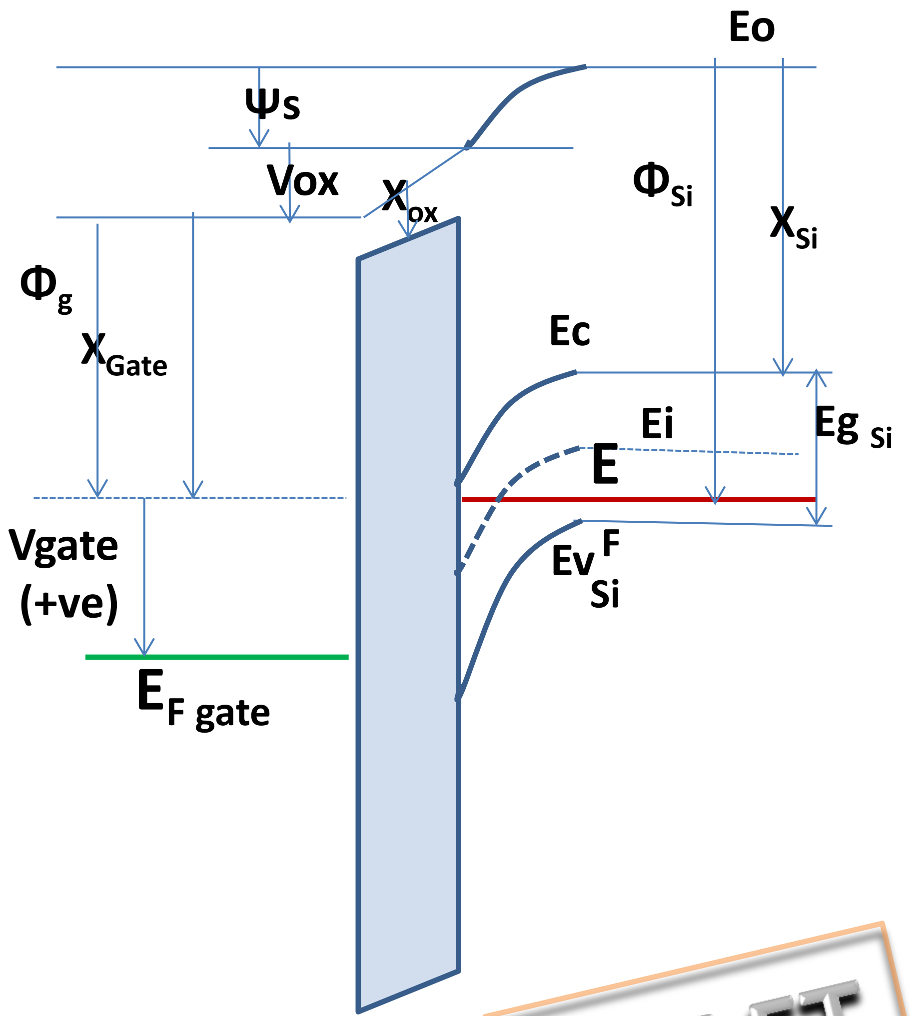
$$V_{ox} = -\frac{Q_s}{C_{ox}}$$

Potential Drop Equation: Applied Gate Voltage

$$V_g + (\Phi_{si} - \Phi_g) = V_{ox} + \Psi_s$$

$$V_g - V_{FB} = V_{ox} + \Psi_s$$

$$V_{ox} = -\frac{Q_s}{C_{ox}}$$



In Inversion:

$$Q_s = Q_{dep} + Q_{inv}$$

$$Q_{dep} = -qN_A W_{dep} = -\sqrt{2\epsilon_{si} q N_A \Psi_s}$$

In Strong Inversion:

$$Q_{inv} \approx -\sqrt{\frac{2\epsilon_{si} K_B T\, n_i^2}{N_A} e^{\frac{q\psi_s}{2K_B T}}}$$

In-between: use Q_s equation

In Depletion: $Q_s \approx Q_{dep}$

Threshold Voltage (V_{th}) under Depletion Approximation

At $0 > \Psi_s \geq 2\,\Psi_{Bulk}$:

- No free carriers (i.e. no inversion electrons)
- Only depletion charges from ionized dopants

At $\Psi_s \geq 2\,\Psi_{Bulk}$:

- No more changes in surface potential
- Fixed Q_{dep}
- Only changes in inversion electrons
- V_{gate} at $\Psi_s \geq 2\,\Psi_{Bulk}$ is called Threshold Voltage (V_{th})

Using: $V_{gate} = V_{FB} - \frac{Q_s}{C_{ox}} + \Psi_s$

At "Onset" of Strong Inversion: $V_{th} = V_{FB} - \frac{Q_{dep}}{C_{ox}} + 2\Psi_{Bulk}$

$$= V_{FB} + \frac{\sqrt{2\varepsilon_{si} q N_A (2\Psi_{Bulk})}}{C_{ox}} + 2\Psi_{Bulk}$$

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Inversion Charge(V_{th}) under Depletion Approximation

In Strong Inversion ($V_g > V_{th}$):

$$V_{gate} = V_{FB} - \frac{Q_{dep} + Q_{inv}}{C_{ox}} + 2\Psi_{Bulk} = V_{FB} - \frac{Q_{dep}}{C_{ox}} + 2\Psi_{Bulk} - \frac{Q_{inv}}{C_{ox}}$$

$$V_{gate} = V_{th} - \frac{Q_{inv}}{C_{ox}}$$

$$\rightarrow \boldsymbol{Q_{inv}} = -\boldsymbol{C_{ox}}(V_{gate} - V_{th})\boldsymbol{C_{ox}}$$

Capacitance-Voltage (C-V) Characteristics

Small Signal: $C_C(Vg) = dQ_C/dV_C$